What is claimed is:

1   1. A phase and frequency tracking apparatus for multi-
2 carrier systems, comprising:
3   an mth-order tracking loop for computing a phase
4   tracking value, a normalized frequency tracking
5   value and a normalized acceleration tracking
6   value for a current symbol based on a phase
7   estimate of said current symbol and a plurality
8   of loop parameters;
9   a frequency predictor for calculating as output a
10   feedback compensation frequency for a next symbol
11   based on an equivalent feedback delay, said
12   normalized frequency tracking value and said
13   normalized acceleration tracking value of said
14   current symbol; and
15   a pre-DFT synchronizer for compensating the phase and
16   frequency of a received signal in a time domain
17   using said feedback compensation frequency before
18   taking an N-point Discrete Fourier Transform
19   (DFT).

1   2. The apparatus as recited in claim 1 wherein said
2 mth-order tracking loop is a third-order tracking loop
3 modeled with a set of recursive equations, as follows:

$$\phi_{T,i} = \phi_{P,i} + \mu_{\phi,i}\phi_{\varepsilon,i}$$
4
$$\Omega_{T,i} = \Omega_{P,i} + \mu_{f,i}\phi_{\varepsilon,i}$$
$$a_{T,i} = a_{T,i-1} + \mu_{a,i}\phi_{\varepsilon,i}$$

5 and

$$\phi_{P,i+1} = \phi_{T,i} + \Omega_{T,i}$$
$$\Omega_{P,i+1} = \Omega_{T,i} + a_{T,i}$$

where

subscript i denotes a symbol index,

$\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$ respectively denote said phase, said normalized frequency and said normalized acceleration tracking values of symbol i,

$\mu_{\phi,i}$, $\mu_{f,i}$ and $\mu_{a,i}$ respectively denote said loop parameters of the ith symbol for $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

$\phi_{P,i}$ and $\Omega_{P,i}$ respectively denote a phase prediction value and a normalized frequency prediction value of the ith symbol,

$\phi_{P,i+1}$ and $\Omega_{P,i+1}$ are said phase and said normalized frequency prediction values of symbol $i+1$,

$a_{T,i-1}$ is said normalized acceleration tracking value of symbol $i-1$,

and $\phi_{\varepsilon,i}$, a phase prediction error of the ith symbol, is given by:

$$\phi_{\varepsilon,i} = \phi_{E,i} - \phi_{P,i}$$

where $\phi_{E,i}$ denotes said phase estimate of the ith symbol.

3. The apparatus as recited in claim 2 wherein initial values of said phase, said normalized frequency and said normalized acceleration tracking values, $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$, are set to zero, for $i = -1$; said loop parameters $\mu_{f,i}$ and $\mu_{a,i}$ are equal to zero, for $i = 0$.

4. The apparatus as recited in claim 2 wherein said feedback compensation frequency is calculated for said next symbol from:

4     $$\Omega_{C,i+1} = \Omega_{T,i} + D_f a_{T,i}$$

5 where D_f is a numerical representation of said equivalent

6 feedback delay and $\Omega_{C,i+1}$ is said feedback compensation

7 frequency of symbol i+1.

1   5. The apparatus as recited in claim 1 wherein said

2 pre-DFT synchronizer receives said feedback compensation

3 frequency of the ith symbol, $\Omega_{C,i}$, to compensate the

4 frequency of said received signal and de-rotate the phase of

5 said received signal in the time domain before taking the

6 N-point DFT, by:

7     $$\tilde{r}_i[n] = r_i[n]\, e^{j\Omega_{C,i}\frac{(N-1)-2n}{2N'}} , \quad 0 \le n \le N-1$$

8 where n denotes a sample index, $r_i[n]$ denotes said received

9 signal of sample n of symbol i, and N' is the number of

10 samples in a symbol interval.

1   6. A phase and frequency tracking apparatus for multi-

2 carrier systems, comprising:

3   an mth-order tracking loop for computing a phase

4   tracking value, a normalized frequency tracking

5   value and a normalized acceleration tracking

6   value for a current symbol based on a phase

7   estimate of said current symbol and a plurality

8   of loop parameters, wherein said phase tracking

9   value is employed to compensate for an effect of

10   phase drift; and

11   a frequency predictor for calculating as output a

12   feedback compensation frequency for a next symbol

13   based on an equivalent feedback delay, said

14   normalized frequency tracking value and said

15   normalized acceleration tracking value of said

16   current symbol, whereby pre-DFT synchronization

17   can be accomplished using said feedback

18   compensation frequency.

1   7. The apparatus as recited in claim 6 wherein said

2 phase estimate of said current symbol, $\phi_{E,i}$, is computed from

3 the following function:

4
$$\phi_{E,i} = \text{angle}\left(\sum_{m=1}^{N_{SP}} R'_{i,p_m}\left(H_{p_m} X_{i,p_m}\right)^*\right)$$

5 where

6   superscript * denotes complex conjugation,

7   subscript i denotes a symbol index,

8   N_{SP} is the number of the pilot subcarriers,

9   subscript p_m denotes a pilot subcarrier index, *for*

10         $m = 1, \ldots, N_{SP}$,

11   H_{p_m} denotes said channel response of pilot subcarrier

12   p_m,

13   X_{i,p_m} denotes said transmitted data on pilot subcarrier

14   p_m of symbol i,

15   R'_{i,p_m} denotes said timing compensated version of the ith

16   symbol on pilot subcarrier location p_m, and

17      $\phi_{E,i}$ represents said phase estimate of the ith symbol.

1   8. The apparatus as recited in claim 6 wherein said

2 mth-order tracking loop is a third-order tracking loop

3 modeled with a set of recursive equations, as follows:

4
$$\phi_{T,i} = \phi_{P,i} + \mu_{\phi,i}\phi_{\varepsilon,i}$$
$$\Omega_{T,i} = \Omega_{P,i} + \mu_{f,i}\phi_{\varepsilon,i}$$
$$a_{T,i} = a_{T,i-1} + \mu_{a,i}\phi_{\varepsilon,i}$$

5 and

6
$$\phi_{P,i+1} = \phi_{T,i} + \Omega_{T,i}$$
$$\Omega_{P,i+1} = \Omega_{T,i} + a_{T,i}$$

7   where

8   subscript i denotes a symbol index,

9        $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$ respectively denote said phase, said

10   normalized frequency and said normalized

11   acceleration tracking values of symbol i,

12       $\mu_{\phi,i}$, $\mu_{f,i}$ and $\mu_{a,i}$ respectively denote said loop

13   parameters of the ith symbol for $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

14       $\phi_{P,i}$ and $\Omega_{P,i}$ respectively denote a phase prediction

15   value and a normalized frequency prediction value

16   of the ith symbol,

17       $\phi_{P,i+1}$ and $\Omega_{P,i+1}$ are said phase and said normalized

18   frequency prediction values of symbol $i+1$,

19       $a_{T,i-1}$ is said normalized acceleration tracking value of

20   symbol $i-1$,

21   and $\phi_{\varepsilon,i}$, a phase prediction error of the ith symbol, is given

22   by:

23       $$\phi_{\varepsilon,i} = \phi_{E,i} - \phi_{P,i}$$

24   where $\phi_{E,i}$ denotes said phase estimate of the ith symbol.

1   9. The apparatus as recited in claim 8 wherein initial

2   values of said phase, said normalized frequency and said

3   normalized acceleration tracking values, $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

4   are set to zero, for $i=-1$; said loop parameters $\mu_{f,i}$ and $\mu_{a,i}$

5   are equal to zero, for $i=0$.

1   10. The apparatus as recited in claim 8 wherein said

2   feedback compensation frequency is calculated for said next

3   symbol from:

4      $$\Omega_{C,i+1} = \Omega_{T,i} + D_f a_{T,i}$$

5   where D_f is a numerical representation of said equivalent

6   feedback delay and $\Omega_{C,i+1}$ is said feedback compensation

7   frequency of symbol $i+1$.

1   11. The apparatus as recited in claim 6 wherein said

2   feedback compensation frequency of the ith symbol, $\Omega_{C,i}$, is

3   provided as feedback to de-rotate a received signal prior to

4   taking the N-point DFT, by:

5      $$\tilde{r}_i[n] = r_i[n]\, e^{j\Omega_{C,i}\frac{(N-1)-2n}{2N'}} \,, \quad 0 \le n \le N-1$$

6   where n denotes a sample index, $r_i[n]$ denotes said received

7   signal of sample n of symbol i, and N' is the number of

8   samples in a symbol interval.

1   12. A phase and frequency drift compensation apparatus

2   for multi-carrier systems, comprising:

3   a timing offset compensator for receiving a current

4   symbol in a frequency domain after taking an N-

5   point Discrete Fourier Transform (DFT) and

6   compensating for a timing offset in said current

7   symbol;

8   a phase estimator for taking a timing compensated

9   version of said current symbol on pilot

10   subcarrier locations and computing a phase

11   estimate for said current symbol based on a

12   function of a channel response of each pilot

13   subcarrier, transmitted data on each pilot

14   subcarrier, and said timing compensated version

15   of said current symbol on said pilot subcarrier

16   locations;

21

17   .   an *m*th-order tracking loop for computing a phase

18   tracking value, a normalized frequency tracking

19   value and a normalized acceleration tracking

20   value for said current symbol based on said phase

21   estimate of said current symbol and a plurality

22   of loop parameters;

23   a frequency predictor for calculating as output a

24   feedback compensation frequency for a next symbol

25   based on an equivalent feedback delay, said

26   normalized frequency tracking value and said

27   normalized acceleration tracking value of said

28   current symbol;

29   a pre-DFT synchronizer for compensating the phase and

30   frequency of a received signal in a time domain

31   using said feedback compensation frequency before

32   taking the *N*-point DFT; and

33   a phase compensator for compensating said timing

34   compensated version of said current symbol for an

35   effect of phase drift with said phase tracking

36   value of said current symbol.

1   13. The apparatus as recited in claim 12 wherein said

2 *m*th-order tracking loop is a third-order tracking loop

3 modeled with a set of recursive equations, as follows:

$$\phi_{T,i} = \phi_{P,i} + \mu_{\phi,i}\phi_{\varepsilon,i}$$

4    $$\Omega_{T,i} = \Omega_{P,i} + \mu_{f,i}\phi_{\varepsilon,i}$$

$$a_{T,i} = a_{T,i-1} + \mu_{a,i}\phi_{\varepsilon,i}$$

5 and

6    $$\phi_{P,i+1} = \phi_{T,i} + \Omega_{T,i}$$

$$\Omega_{P,i+1} = \Omega_{T,i} + a_{T,i}$$

7 where

8   subscript i denotes a symbol index,

9      $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$ respectively denote said phase, said

10   normalized frequency and said normalized

11   acceleration tracking values of symbol i,

12      $\mu_{\phi,i}$, $\mu_{f,i}$ and $\mu_{a,i}$ respectively denote said loop

13   parameters of the ith symbol for $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

14      $\phi_{P,i}$ and $\Omega_{P,i}$ respectively denote a phase prediction

15   value and a normalized frequency prediction value

16   of the ith symbol,

17      $\phi_{P,i+1}$ and $\Omega_{P,i+1}$ are said phase and said normalized

18   frequency prediction values of symbol $i+1$,

19      $a_{T,i-1}$ is said normalized acceleration tracking value of

20   symbol $i-1$,

21 and $\phi_{\varepsilon,i}$, a phase prediction error of the ith symbol, is given

22 by:

23      $$\phi_{\varepsilon,i} = \phi_{E,i} - \phi_{P,i}$$

24 where $\phi_{E,i}$ denotes said phase estimate of the ith symbol.

1   14. The apparatus as recited in claim 13 wherein

2 initial values of said phase, said normalized frequency and

3 said normalized acceleration tracking values, $\phi_{T,i}$, $\Omega_{T,i}$ and

4 $a_{T,i}$, are set to zero, for $i=-1$; said loop parameters $\mu_{f,i}$ and

5 $\mu_{a,i}$ are equal to zero, for $i=0$.

1   15. The apparatus as recited in claim 13 wherein said

2 feedback compensation frequency is calculated for said next

3 symbol from:

4      $$\Omega_{C,i+1} = \Omega_{T,i} + D_f a_{T,i}$$

5 where D_f is a numerical representation of said equivalent

6 feedback delay and $\Omega_{C,i+1}$ is said feedback compensation

7 frequency of symbol $i+1$.

1   16. The apparatus as recited in claim 12 wherein said

2 pre-DFT synchronizer receives said feedback compensation

3 frequency of the ith symbol, $\Omega_{C,i}$, to compensate the

4 frequency of said received signal and de-rotate the phase of

5 said received signal in the time domain before taking the

6 N-point DFT, by:

7
$$\tilde{r}_i[n] = r_i[n]\, e^{j\Omega_{C,i}\frac{(N-1)-2n}{2N'}} , \quad 0 \le n \le N-1$$

8 where n denotes a sample index, $r_i[n]$ denotes said received

9 signal of sample n of symbol i, and N' is the number of

10 samples in a symbol interval.

1   17. The apparatus as recited in claim 12 wherein said

2 phase estimator computes said phase estimate of said current

3 symbol, $\phi_{E,i}$, by means of the following function:

4
$$\phi_{E,i} = \mathrm{angle}\left(\sum_{m=1}^{N_{SP}} R'_{i,p_m}\left(H_{p_m} X_{i,p_m}\right)^*\right)$$

5 where

6   superscript * denotes complex conjugation,

7   subscript i denotes a symbol index,

8   N_{SP} is the number of the pilot subcarriers,

9   subscript p_m denotes a pilot subcarrier index, *for*

10         $m = 1, ..., N_{SP}$,

11   H_{p_m} denotes said channel response of pilot subcarrier

12   p_m ,

13   X_{i,p_m} denotes said transmitted data on pilot subcarrier

14   p_m of symbol i,

15   R'_{i,p_m} denotes said timing compensated version of the ith

16   symbol on pilot subcarrier location p_m, and

17    $\phi_{E,i}$ represents said phase estimate of the ith symbol.

1   18. A phase and frequency tracking apparatus for multi-

2   carrier systems, comprising:

3   a pre-DFT synchronizer for compensating the phase and

4   frequency of a received signal in a time domain

5   using a feedback compensation frequency before

6   taking an N-point Discrete Fourier Transform

7   (DFT).

1   19. The apparatus as recited in claim 18 wherein said

2   pre-DFT synchronizer receives said feedback compensation

3   frequency of the ith symbol, $\Omega_{C,i}$, to compensate the

4   frequency of said received signal and de-rotate the phase of

5   said received signal in the time domain before taking the

6   N-point DFT, by:

7    $$\tilde{r}_i[n] = r_i[n]\, e^{j\Omega_{C,i}\frac{(N-1)-2n}{2N'}} , \quad 0 \le n \le N-1$$

8   where n denotes a sample index, $r_i[n]$ denotes said received

9   signal of sample n of symbol i, and N' is the number of

10   samples in a symbol interval.